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A high speed, teleoperated unmanned ground vehicle (UGV) was recently demonstrated in United States Marine Corps operational exercises at Camp Pendleton, California. Advanced features of the human-machine interface components used in the remote vision systems are credited with allowing both novice and experienced operators to effectively perform UGV tasks. The UGV was remotely guided across terrain ranging from smooth asphalt to severe undeveloped land at velocities up to 60 kilometers per hour. Reconnaissance, surveillance and target acquisition tasks were remotely completed using UGV remote vision systems.

Off-road exercises were conducted to gain an understanding of how UGV system operation is affected by variations in visual display system features. Observations on the utility of features such as stereoscopic vision, color imagery, head-mounted displays, and head-coupled aiming of sensors are discussed. Recommendations are provided for the design of future UGV remote vision systems.

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REMOTE VISION SYSTEMS FOR TELEOPERATED UNMANNED GROUND VEHICLES

1.0 INTRODUCTION

1.1 Background. The United States Department of Defense (DoD) supports the development of Unmanned Ground Vehicle (UGV) systems for battlefield applications. Three versions of remotely operated UGV systems were recently demonstrated during field exercises administered by the DoD UGV Joint Program Office. [1] These man-in-the-loop systems, called "teleoperated" systems, remove the human operator from the battlefield and offer protection from hazards encountered by the remotely controlled vehicle.

The Naval Ocean Systems Center (NOSC) has a long history in the research and development of remotely controlled vehicles and manipulator systems for undersea, land and space applications. [2] [3] Ongoing research at NOSC focuses on teleoperated systems designed with a characteristic referred to as "remote presence".

> "Remote presence is the perception of actually existing at the remote location. The degree of 'presence' achieved is determined by the fidelity of the sensory feedback to the operator." [2].

Based on NOSC's experience with teleoperated vehicles and research in remote presence principles, remote vision systems were designed to support development of the TeleOperated Vehicle (TOV) system - a United States Marine Corps (USMC) sponsored UGV effort. Lessons learned from this development, and from field tests of TOV vision systems, are presented in this paper.

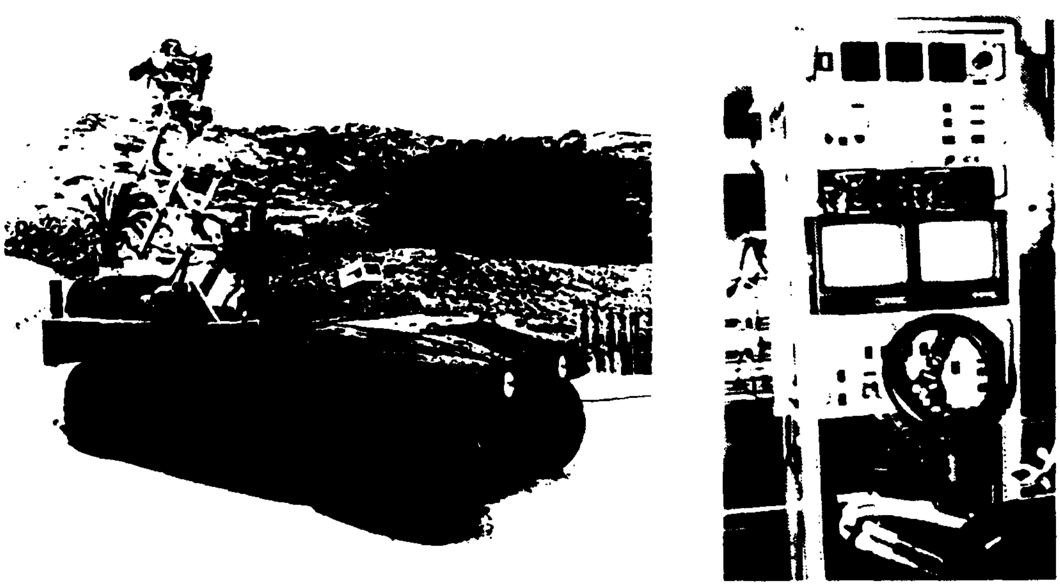

Figure 1. TOV Remote Vehicle (RV) and Control Station (CS).

1.2 TeleOperated Vehicle (TOV). TOV is a remotely operated, unmanned ground vehicle system which permits an operator to extend sensory, motor function and problem solving skills to a vehicle located up to 30 kilometers away. [4] The TOV system consists of a Remote Vehicle (RV) and a Control Station (CS), shown in figure (1). A human operator controls the TOV system using displays and controls located at the CS. Visual and auditory CS displays are designed to facilitate understanding of the RV's situation. Hand- and foot-operated controls, similar to automotive vehicle controls, and head position sensors provide the means of controlling RV functions. A fiber optic data link allows physical separation of the operator from hazards encountered by the RV. The RV, based on the High Mobility Multi-Wheeled Vehicle (HMMWV), is capable of high transit speeds and can traverse severe off-road terrain. Three mission-specific add-on subsystems, called mission modules are accommodated. Surveillance, reconnaissance, and target acquisition are functions which are currently supported by these mission modules.

2.0 TOV VISION SYSTEMS

2.1 Overview. The operator must be kept abreast of changes in the remote environment to effectively control the TOV. Since vision is such an important sense, faithful portrayal of visible surroundings encountered by the remotely located vehicle is paramount. A UGV operator must be able to easily interpret visual sensory data to perform tasks effectively.

TOV vision systems comprise various types of image sensors and displays. Depending on the task, a particular subset of these components may be used. TOV systems make use of two separate display systems, one for driving the remote vehicle and one for mission specific tasks such as reconnaissance, surveillance, and target acquisition (RSTA).

Remote driving is complicated by the inherent unpredictable nature of off-road terrain. Fast, accurate scene interpretation is needed to allow operator reaction to terrain conditions. For these situations a head-mounted stereoscopic display is used in conjunction with head-coupled video sensors on the vehicle.

RSTA tasks typically require slow panoramic scans of the sensors, often at deflection angles that would be difficult to maintain using head-coupled control. Panel mounted video monitors are used in these situations with RSTA sensor pointing direction controlled with a joystick.

2.2 Mobility System. Sensory information required for remote driving of the TOV RV is provided to the operator through the mobility system. The mobility system, depicted in figure 2, is comprised of the mobility sensor platform, located on the RV and the HMD, which is a part of the CS. The mobility system is configured with visual and aural capabilities that give the operator the impression of being present at the remote site. This is accomplished by sensing the remote scene using a stereoscopic camera pair and binaural audio microphones. The pointing direction of these sensors is controlled with operator head position commands.

RV mobility system audio and video information are presented to the operator through the Control Station Head Mounted Display. A head orientation sensor, affixed to the operator's helmet, provides position commands that cause the mobility sensor

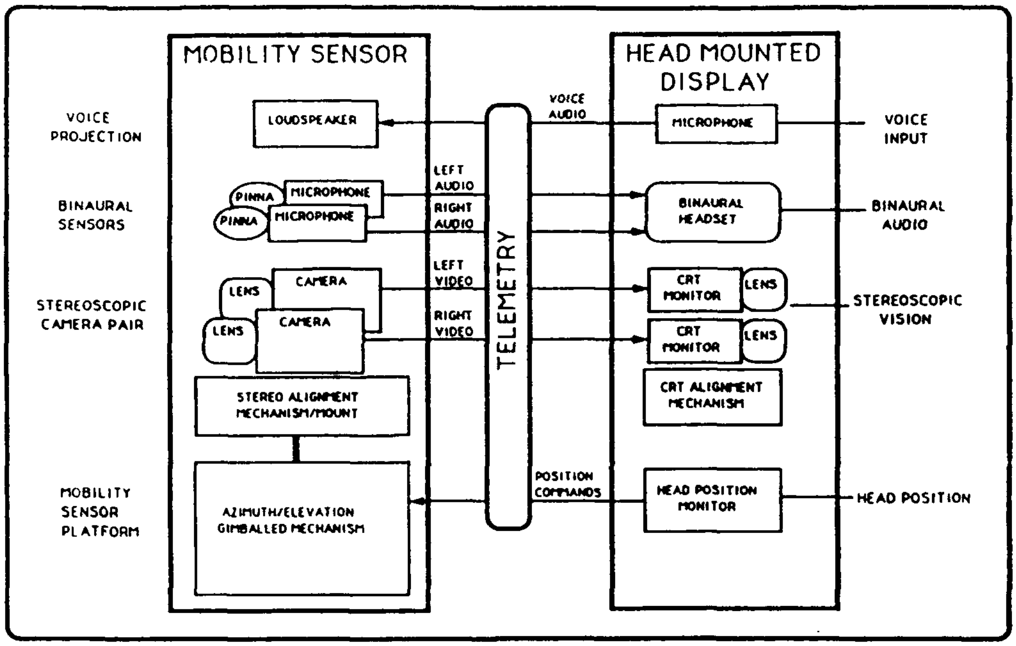

Figure 2. TOV Mobility System Block Diagram.

platform to track the operator head's yaw and pitch orientation with one-to-one correspondence. For instance, if the operator's head turns to the left 30 degrees, the mobility sensor platform deflects its angle to the left by 30 degrees. In this manner, sensors located on the remote motorized platform are aimed using head-coupled control.

2.3 Surveillance/Weapon System. Sensory information required to support mission specific tasks is supported through modular additions to the TOV system. Two modules that are implemented are the Reconnaissance, Surveillance and Target Acquisition (RSTA) and weapon modules. Each of these modules has azimuth/elevation motorized mechanisms. The weapon module is mounted on a pedestal and has the capability of slewing an M-2 50 caliber machine gun through a range of positions. The RSTA module has a sensor suite mounted on top of a variable height extendable mast. There is provision to slave the aim of the weapon module to the RSTA module settings. A single joystick is used to control the pointing direction of these modules individually or slaved together.

The weapon module has a single video camera mounted parallel to the weapon barrel. This camera is used to supplement safe operating procedures by providing visual confirmation of weapon aim and by allowing assessment of weapon operation.

RSTA sensors include a surveillance targeting camera with motorized zoom lens, a forward looking infrared (FLIR) camera, and a laser ranging/designator camera. These sensors are integrated onto the RSTA motorized gimbal platform.

Panel mounted displays provide the operator with mission module video imagery. Depending on the circumstances of the mission, the operator is free to select images from any two of the RSTA or weapon video sensors for display.

3.0 TEST AND EVALUATION

3.1 Operational Testing. TOV systems, equipped with RSTA and weapon modules, were extensively tested with U. S. Marine Corps personnel during a series of operations that assessed the viability of TOV remote control concepts. Five phases of tests, involving two TOV systems and numerous civilian and U. S. Marine Corps operators, allowed NOSC engineers to experiment with alternate vision system configurations. During these trials, experts in the field of UGV vision systems were invited to participate in operational tests in order to solicit recommendations for system improvement.

Occasionally, unscheduled demonstrations of TOV systems occurred during the course of testing. Individuals without TOV experience were encouraged to participate in limited driving runs. Virtually all novice operators were able to operate the TOV after only a few minutes of instruction. Comments obtained from these drivers and observations of their experiences provided additional information to system designers and are discussed in this paper.

TOV systems were successfully driven over terrain ranging from smooth asphalt to severe undeveloped land. Remote vehicle velocities in excess of 60 km/hr were common with typical driving speeds of 25 km/hr over dirt and gravel roads.

In September 1989, an Advanced Technology Transition Demonstration featuring USMC and U. S. Army teleoperated systems was conducted at Camp Pendleton, California. [1] This exercise, coordinated by the UGV Joint Program Office, included the TOV system and the U. S. Army's Teleoperated Mobile All-Purpose Platform (TMAP). Experience gained while preparing for and conducting demonstrations confirmed previous vision system observations.

3.2 Human Factors Experiments. NOSC research scientists have long been involved in human factors studies related to UGV and other teleoperated work systems. [5][6][7] Current research efforts focus on issues:

1) comparing stereoscopic and non-stereoscopic vision systems for driving tasks;
2) comparing driving performance of HMDs and panel mounted display options;
3) comparing color and black-and-white vision systems in selected UGV applications;
4) determining the best compromise between video sensor field of view and display resolution for UGV tasks.

4.0 DISCUSSION OF REMOTE VISION SYSTEM FEATURES

4.1 Stereoscopic Vision refers to the strong sense of three-dimensional depth perception derived from retinal disparity cues (differences between left-eye and right-eye retinal images, arising from the eye's horizontal separation). Retinal disparity is only one of many cues used for depth perception, but it is one of the strongest and least ambiguous sources of information about relative position in three-dimensional space. The visual system in the brain analyzes binocular parallax between the left and right retinal images, (along with many other visual and non-visual cues) to infer the three-dimensional location of surfaces and objects in the scene.

A stereoscopic video sensor and display system typically uses two cameras (separated horizontally by the nominal human eye offset of 65 mm) to "stand in" for the observer's left and right eyes, picking up two different two-dimensional images that are transmitted by the display system to the observer's own left and right retinas. The visual system in the brain then treats these images as normal visual input, as if the retinal images had been obtained by looking directly at the scene. The brain uses these two retinal images as information sources for creating a three-dimensional model the scene.

Studies that compare stereoscopic video systems with monoscopic video systems for remote manipulation tasks revealed the positive impact of stereoscopic video on operator learning and in poor visibility conditions. [6][8] From these studies several conclusions have been drawn. Hightower, et al [2] report that stereoscopic television displays provide substantial performance advantages over conventional television displays when:

1) aspects of the remote scenes are unfamiliar or are frequently changing;
2) the rate of learning of new tasks is important;
3) image quality is poor;
4) tasks have significant depth positioning requirements.

Properly implemented, stereoscopic video systems contribute to visual realism, enhancing the operator's sense of remote presence at the teleoperated vehicle's location.

TOV is designed with stereoscopic vision for vehicle mobility operations. This approach is justifiable when one considers the difficulty of maneuvering a remote vehicle at speeds up to 80 kilometers per hour through unfamiliar off-road terrain. It is essential that the operator have the means to detect obstacles and terrain features which may prevent safe vehicle passage. In addition, the RV may encounter poor visibility conditions caused by smoke, fog, dust, vegetation, and low light illumination. In these situations, stereoscopic depth perception provides additional visual cues to the human operator and enhances the operator's chances of successfully completing driving tasks.

TOV has two miniature, high resolution video cameras that provide stereoscopic image sensing. These cameras are aligned with parallel optical axes and are separated a distance equivalent to an average human's interocular separation. The video camera lens field of view (FOV) is selected to match the apparent display FOV observed by the operator. Automatic iris lenses allow unattended aperture adjustment.

An HMD is used as the TOV stereoscopic display. The HMD provides separate left- and right-eye displays corresponding to the left and right video cameras. Since the apparent HMD FOV nearly matches the video camera/lens FOV, an image magnification of approximately 1.0 is realized.

Camera convergence distance was selected through experimentation. Initial remote driving tests were performed with video cameras aligned for convergence 8 meters in front of the vehicle's hood. The rationale for this alignment was that such a configuration would enhance depth perception in the immediate vicinity of the RV. However, in prolonged instances of remote driving, operators reported perceptual discomfort when viewing distant objects on the horizon. This may be explained by the need to diverge the eyes, beyond parallel, in order to fixate objects further than 8 meters. Since eye divergence is not normal, operator fatigue results due to eye strain.

For subsequent tests, the camera optical axes were aligned parallel to each other (converged at infinity). Eye convergence, when using the HMD in this configuration, is nearly identical to eye convergence when viewing the remote scene directly. Eye divergence is not required to fuse any of the objects within view. There were no further reports of viewing discomfort following this adjustment.

The stereoscopic effect is important to remote driving, especially near the vehicle. This area is of immediate concern with regard to obstacles and terrain features.

RV remote driving trials were recorded using videotape and still photographs. Analyses of these recordings revealed that objects, such as rocks buried in vegetation, and negative terrain features such as potholes and ditches, were difficult and sometimes impossible to discern using monoscopic vision. Stereoscopic views of the same scene increased the detectability of these hazards.

4.2 Color Imagery. TOV remote vision systems were initially designed to support black-and-white sensors and displays. Several factors influenced this decision to exclude color imagery. First, there were no definitive references that favored color images for remote vehicle driving and tactical missions. Further, the high cost and increased complexity to support color imagery in low light illumination precluded its use at night. Finally, the technology to support color head-mounted displays for driving were not adequately developed.

Despite the original decision not to include color cameras and color CRT monitors, NOSC engineers designed TOV telemetry electronics to be compatible with color video (NTSC) standards. This permitted TOV system experimentation with a color surveillance zoom camera and color panel mounted display. Anecdotal data from TOV operators indicate that in certain RSTA situations, color improved operator recognition of targets. However in poor lighting situations, such as near dusk and in shadows, recognition of targets was degraded due to color sensor limitations.

Videotape segments of TOV driving exercises and segments using hand-held video camcorders were compiled to observe whether color imagery contributes to effective remote driving. Anecdotal data indicate that color rendition of certain terrain features enhances operator recognition of those features. For example, dirt roads lined with vegetation stood out in color because of the contrast between the brown path and green borders. Wet and burned vegetation were more noticeable when viewed in color. Rocks hidden in tall grass blended in with shadows when viewed in black-and-white, but were recognizable as distinct objects when color was added.

Practical implementation of color vision systems is limited by technology. Low light level video cameras are not inexpensively available to support color. In addition, color HMD technology is not readily available to support a full color, moderate resolution and field of view display. System complexity is increased by the need to sense, transmit and display color images. It is clear that further experimentation is needed to assess the performance tradeoffs associated with color/non-color sensor and display possibilities.

4.3 Terrain Slope Perception. Operator perception of remote vehicle attitude is essential to complete certain UGV driving maneuvers. Pitch and roll attitude cues provide operators with an understanding of vehicle state and terrain grade/slope. This data, combined with knowledge of vehicle driving characteristics, allows the operator to decide whether transit through encountered terrain is advisable or even possible. Without proper attitude awareness, the operator lacks crucial information needed to effectively negotiate off-road terrain. For example, if the operator fails to recognize severe terrain slopes, the remote vehicle may be driven inappropriately on steep hills, resulting in vehicle roll-over.

TOV system drivers gain an understanding of remote vehicle pitch and roll attitude through observation of HMD video information. Pitch and roll alphanumeric indicators are also accessible but are not normally used while driving. The mobility sensor platform is positioned on the vehicle so that the remote vehicle's hood is normally in view at the bottom of the display screen. Since the mobility sensor platform's roll axis is fixed, relative to the vehicle, the vehicle's hood is normally displayed with its top edge horizontal to the display screen. When the vehicle's attitude is affected by terrain, the change in vehicle attitude is portrayed through changes in displayed terrain features. For example, if the vehicle is on a side slope, then trees that are displayed in the video monitors will tilt to one side. In contrast, visible parts of the remote vehicle retain a fixed attitude in the display. This frame of reference may be termed "vehicle referenced" since the cameras are referenced to the vehicle's normal axis, and the displayed vehicle attitude remains constant.

When viewing vehicle referenced displays, it is easy for operators to mistakenly perceive the vehicle to be oriented upright, regardless of the actual orientation. Unless the operator has unambiguous visible attitude references, such as landmarks or the horizon, disorientation can result. This is especially true under degraded viewing conditions. If the operator is incapable of seeing more than a few meters past the vehicle, it would be difficult to interpret vehicle attitude.

During TOV operations and tests, operators occasionally experienced a distorted sense of RV attitude. In these situations, they were not able to understand RV pitch/roll attitude without protracted visual analysis of the display. During dynamic driving conditions, when vehicle attitude is constantly changing, the lack of adequate attitude awareness may lead to dangerous driving situations.

Real-life examples highlight the operator's difficulty to recognize RV pitch and roll attitude. While conducting tests, the RV was occasionally driven and parked on terrain side slopes. In several instances when normally upright objects, such as utility poles or test personnel, came into view, operators were surprised to see them standing at a severe angle. Upon further pondering, operators reported that they were forced to accept the fact that the objects were vertical and that the RV was on an incline. If UGV operators are so easily misled, hazardous terrain conditions may be incorrectly interpreted and may threaten the effectiveness of the UGV system.

To study this effect, NOSC scientists initiated a series of experiments and considered possible remedies. Of particular interest are methods that make the operator intuitively aware of remote vehicle attitude. Promising approaches include the superposition of graphical symbology to the driving video display, motion simulation feedback to the operator's seat, and the use of "gravity referenced" compensation to video sensors.

Gravity referenced compensation keeps the video sensors at a constant pitch and roll orientation with respect to the earth's gravity. The mechanism maintains its gravity reference independent of the vehicle's attitude. As a result, the image of the vehicle's hood is observed to pitch and roll as the vehicle's attitude is affected by terrain conditions. This tends to serve as a natural visual indicator of vehicle attitude.

Videotape simulations using video cameras demonstrate the advantage of the gravity referenced sensor principle. Scenes were recorded using a video camcorder located near the vehicle's driving cameras. The vehicle was driven through a course with severe grade and side slope. When taping the vehicle referenced version, the camera was held against the vehicle roll bar to maintain a fixed camera view relative to the vehicle. During gravity referenced trials, the hand-held camcorder was continuously adjusted to maintain a gravity referenced position.

It was observed that the gravity referenced view of the course provided more readily interpretable vehicle pitch and roll attitude cues. The changing vertical position of the vehicle's hood within the display, provided an indication of changing terrain grade.

Similarly, terrain side slopes were perceived through vehicle hood tilt angles across the display screen. In addition to providing positive indication of vehicle attitude, terrain texture was more readily discernable through observation of vehicle hood vibrations.

As a result of these observations, NOSC has initiated studies to determine how best to present remote vehicle attitude information to the operator.

4.4 Head-Coupled Aiming of Sensors. Head-coupled aiming of driving sensors distinguish the TOV system from other teleoperated vehicles systems intended for military field operation. Operator pitch and yaw head orientation is sensed and used to aim the mobility sensor platform's pitch and yaw orientation. Head-coupled slaving of the mobility sensor platform give the operator intuitive knowledge of where the video cameras are aimed in three-dimensional space.

Head coupling of the TOV mobility system is implemented as follows. An electromagnetic sensor affixed to the TOV operator's helmet senses operator's head orientation and generates commands that are transmitted to the Remote Vehicle. There, these commands are used to adjust the pitch and yaw orientation of a multi-axis, motorized, gimballed sensor platform that contains the stereoscopic vision and binaural sensors. Changes in the remote visual aspect, due to sensor platform movements, are viewed by the operator through miniature CRT monitors attached to a helmet. Thus, operator pitch/yaw head movements are designed to modify the sensor platform viewing angle such that an one-to-one spatial correspondence between head and platform is achieved.

This TOV feature has several benefits. Head-coupled aiming control of the stereoscopic cameras promotes the remote presence sensation. This may result in reduced training time and easier, natural control of camera views. The operator is able to scan the entire visual hemisphere using simple head scans and nods, and while retaining high resolution viewing in the line of sight. This is possible while automatically retaining spatial correspondence of objects to the vehicle. Proprioception, or the awareness of neck and body position, while locating objects allows the operator to remember where those objects lie in three dimensional space. An additional benefit of head-coupled aiming of sensors is that it keeps the operator's hands and attention free to tend to other tasks, such as steering the vehicle.

TOV operators were able to take advantage of this feature in several ways. Most operators are quick to learn the concept of head-coupled camera control. It was observed that operators use the head coupling feature effectively to monitor the condition of the RV, to scan the local terrain while driving, and to fixate on auditory and visual targets. Although vehicle condition status reports are available through the TOV panel mounted display, several operators reported that it was more comforting to see video confirmation of shift lever position, brake pedal position, and other controls by remote observation of these controls, rather than status displays derived from actuator sensors. It was also observed to be very easy to head-aim the camera toward the RV function of interest since spatial position correspondence of objects were similar to what one would expect when directly driving the vehicle. While conducting remote driving trials, operators were observed to use head coupling of the cameras to scan the local terrain. This is especially important when making sharp turns. Operators are able to confidently and accurately negotiate turns because they are able to view and anticipate where they are headed. Head coupling also provides the benefit of locating and turning to visual and auditory targets with relative ease. Proprioceptive sensing allows operators to find previously located targets through correlation of object location with operator neck position. Gross tracking of visual targets using head coupling is maintained through head movements. Auditory tracking of targets is also possible through the use of the binaural audio sensors and head coupling.

Perceptual cue conflicts, attributable to the implementation of the TOV head coupling scheme, were observed during testing. A combination of head sensing, platform actuation, video, and telemetry delays contribute to the overall perception that the image lags rapid head motions. The perception that video imagery lags the head motion has a range of effects on TOV operators and performance. This perceptible lag is usually noticeable by the operator but is often ignored during driving operations. Some operators are annoyed and even discomforted by the lag. More responsive head tracking sensors and remote platforms [9] may be used to reduce this source of discomfort.

4.5 Head-Mounted Displays (HMD) are designed to be worn on the operator's head. Since the displays move with the operator's head, this configuration keeps the visual display in sight while allowing unrestricted head movements. When used in conjunction with head position tracking systems, HMDs can provide a natural, hands free method of aiming video sensors.

TOV HMDs have a pair of video monitors to provide binocular viewing using separate left- and right-eye displays. The video monitors accept EIA RS-170A or NTSC video signals, and convert them to visual images. Video resolution, overall video display size and weight are some of the critical factors used to evaluate monitors. Telescope eyepieces are used to magnify the images from the CRT monitor, which are placed directly in front of the operator's eyes. When used with a 19 mm diagonal CRT image, the apparent field of view to the operator is 40 degrees. When used with a 25 mm diagonal CRT image, the apparent field of view is 55 degrees.

The CRT stereo alignment mechanism secures the CRTs in front of the operator's eyes. They are intended to be aligned for full (100 percent) binocular overlap and such that the CRTs optical axes are parallel to each other. A modified aviator's night vision system (AN/AVS-6) binocular assembly is used to provide these functions through four

Figure 3. TOV Head Mounted Display.

vernier knob controls (up/down, interocular separation, in/out, tilt). The helmet, onto which the stereo alignment mechanism is mounted, is a standard U. S. Army combat vehicle crewman helmet, model DH-132A.

Two versions of HMDs were developed to support TOV exercises. [10] One implementation, shown in figure 3, provides high resolution (700 horizontal television lines per picture height (HTVL/PH)) video displays with moderate FOV (40 degrees horizontal). The second uses alternate CRT's that resolves 250 HTVL/PH with a wider FOV (55 degrees horizontal). During operational evaluation, the mobility system camera lenses are changed to match to the HMD FOV. These lenses are matched to the display such that the sensor and display FOVs are nearly equivalent. For example, if the HMD provides 40 degrees FOV, then the camera lens focal length is selected to provide 40 degrees FOV. Table 4.1 lists HMD parameters and corresponding camera lens focal lengths. The equivalent visual acuity for these vision systems was calculated and verified through experimentation. It was estimated that visual acuity for the higher resolution HMD is 20/95 and 20/155 for the lower resolution HMD. By comparison, many U. S. driving laws require corrected visual acuity of 20/40 or better.

Table 1. TOV HMD Visual Acuity.

	HMD Apparent FOV	
	40 degrees	55 degrees
Camera Lens (focal length)	12.5 mm	8 mm
Horizontal Display Resolution	700 HTVL/PH	250 HTVL/PH
Vertical Display Resolution	350 TV lines	350 TV lines
Equivalent Visual Acuity	20/95	20/155

The lack of high visual acuity and the relatively narrow FOV are among the common complaints with TOV drivers. Operators desire higher image resolution to perform more detailed inspection of targets. Most operators also want a wider field of view so that an instantaneous view of the entire vehicle's hood is possible. With 40 degrees FOV, it is possible to see the entire hood only by scanning left and right. This exercise is tedious when maneuvering near obstacles since the operator is required to constantly scan back and forth in order observe both extremes of the vehicle hood. However, TOV drivers indicated that head-coupled scans were useful in retaining spatial awareness of the vehicle and its obstacles during these maneuvers. The 55 degrees FOV system provided better peripheral FOV at the expense of lower image resolution.

Overall, TOV operators favored the HMD with a moderate 40 degrees FOV and high resolution. They compensated for the limited FOV with more head scans. The HMD configuration was also extensively exploited to view the entire visual hemisphere using head motion.

In order to combine the benefits of the moderate FOV display with high image resolution, it is proposed that a telescopic camera be co-located with the stereo camera pair. The operator would be provided the capability of instantly switching between viewing of the stereo pair and telescopic cameras. The telescopic camera would be aligned so that it magnifies the central viewable region of the stereo pair image, and provides a biocular view to the operator.

4.6 Alternate Vision Systems. Alternate vision system concepts, using head-coupled aiming of sensors, have been considered for UGV application. Two of the promising approaches are the "virtual window" and "panoramic window" concepts.

The virtual window display is a panel mounted display that uses operator head position to adjust the viewing position of the remote video sensors. The underlying concept is to provide the operator with a view of the remote scene through a simulated window. The display represents the window opening and the operator may peer through the window from different viewing perspectives, through horizontal or vertical head adjustments.

During field exercises at Camp Pendleton, a mock up virtual window was constructed to test this idea. A hole, the size of a 43 cm diagonal CRT was cut out of a large cardboard sheet. The cardboard was mounted in the driver's compartment of a HMMWV and the viewport was positioned to accommodate the vehicle driver. Several kilometers of the test course were driven in this manner. For most driving situations, the mock up virtual window provided adequate viewing coverage. However, since it was not possible to look more than 90 degrees to each side of the vehicle's center, approaching and crossing intersections was a challenge.

The panoramic window display uses multiple video displays arranged in a circle around the operator. In one embodiment, a corresponding circular array of video cameras provide images to the video displays. This arrangement provides instantaneous coverage of the entire 360 degrees FOV. The operator can view any part of this by turning to look at the video display of interest. However, practical limitations of video signal transmission prevents simultaneous real-time updates of all images. The panoramic window concept requires transmission of only a single video signal (or stereoscopic pair). Images from that signal are painted onto the video monitors only in the direction of the operator's gaze. The video sensor's line of sight is slaved to the orientation of the operator's head. This presents an illusion of moving the viewport panoramically around the operator based on head position.

Hardware supporting the panoramic window concept has been developed but has not been tested with UGV systems.

5.0 SUMMARY AND RECOMMENDATIONS

A UGV remote vision system has been developed incorporating stereoscopic vision, head-coupled aiming of sensors, head-mounted displays, and color imagery. This implementation builds on NOSC's past experience with remotely controlled vehicles, manipulator work systems and remote presence research. The vision system allowed operators to remotely maneuver the TOV RV over dirt roads at velocities in excess of 60 km/hr with typical driving speeds of 25 km/hr. Furthermore, the advanced vision system features appeared to reduce operator training time, permitting system operation after only a few minutes of instruction.

Field exercises of TOV systems identified areas for vision system improvement. The lack of adequate RV attitude awareness is recognized as one of the more serious obstacles to optimal system performance. Image resolution and sensor platform mechanism response are other areas that need to be evaluated.

Investigation of the following vision system features, for UGV applications, is recommended:

1) stereoscopic vision;
2) color imagery;
3) terrain slope perception cues;

4) head-coupled aiming of sensors.

It is believed that further studies will confirm the benefit of these features for the UGV driving task.

Stereoscopic vision studies should be initiated to quantify the benefit of binocular depth perception to the off-road driving task. It is recommended that the studies include the impact of depth perception under conditions of degraded image quality. For example, FLIR and low light level video imagers have limited sensing resolution. While one FLIR image may be unintelligible, a FLIR stereo pair may dramatically enhance one's perception of objects in view.

Similarly, the benefit of color imagery should be systematically investigated. Color adds a dimension which often cannot be recovered through black-and-white renditions. It is believed that target detection and recognition can be improved using color. It is also thought to be useful in the more dynamic task of remote vehicle driving.

More effort is required in the area of terrain slope perception. Unless UGV operators have adequate awareness of the vehicle's pitch and roll state, they are in danger of driving into vehicle roll over situations. Proper application of image motion compensation techniques for attitude awareness may contribute to reduced operator fatigue.

Head-coupled aiming of sensors is a key component of the TOV remote presence configuration. Experiments to determine the importance of hands free aim control, spatial awareness, and the ability to scan a very wide hemispherical area should be conducted. Our experience with TOV indicates that head aiming of sensors is highly desirable and often indispensable.

Panel mounted driving display options including virtual window concepts and scannable panel displays require further development.

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